MAP I-1419-C

DEPARTMENT OF THE INTERIOR
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RESIDUAL AEROMAGNETIC AND INTERPRETATIVE MAPS OF THE PUEBLO 1° X 2° QUADRANGLE, SOUTH-CENTRAL COLORADO

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TO ACCOMPANY MAP I-1419-C

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INTERPRETATION

INTRODUCTION

Magnetic features of the Pueblo quadrangle (lat 38° to 39°N. and long 104° to 106° W.) that are interpreted to be significant in terms of crustal composition and structure are shown on the accompanying map (map *B*). These features are superimposed on an enlarged part of the geologic map of Colorado (Tweto, 1979a) for correlation with the major units of mapped geology. More detailed geology is available on the geologic map of the Pueblo 1° × 2° quadrangle by Scott and others (1978).

Magnetic features that are discussed in this text are shown on the map. Mineral districts from Marsh and Queen (1974) and Vanderwilt and others (1947) are also given. Tables 1 and 2 summarize information for each of the magnetic anomalies and trends. Table 3 summarizes information for each of the mineral districts. Figure 4 shows geographic features and faults referred to in the text.

Estimated elevations of the top of the source (sensor elevation minus computed source depth) for most of the anomalies are included in table 1. The source depths were obtained using the method of Vacquier and others (1951), which assumes that the horizontal length of the steepest gradient for the anomaly is proportional to the depth to the top of the source below the level of the sensor. The proportionality constant depends on the geometry of the magnetic source body and the direction of the Earth's field, but is close to 1.0 in most cases, and the value 1.0 was used here. The computed depths are considered accurate to about 20 percent, which is adequate for distinguishing between near-surface and deeper crustal sources. The steepest gradient lengths were measured from the original data in areas 1, 2, and 3 (see fig. 1) in order to take advantage of the greater detail, hence resolution, available in this data as compared to that in map *A*. Depths were not calculated for anomalies in area 4, where the 8-km flightline spacing is considered too large for accurate resolution of maximum gradients. The estimated source elevation occasionally exceeds the elevation of the topography, but never by more than 20 percent of the depth. This reflects the uncertainty in the estimates and simply indicates near-surface or surface sources

MAGNETIC FEATURES OF THE PUEBLO QUADRANGLE

The following discussion is divided into four sections. The first section presents a magnetic model along profile A′–A″ (fig. 5), which crosses the southwest quarter of the quadrangle from the southwest to northeast. The next three sections discuss the quadrangle according to three areas that are defined here by their different magnetic characteristics. These areas, (1) the ridge-trough area, (2) the Front Range area, and (3) the Great Plains area, are distinguished mainly by the different horizontal dimensions of their magnetic anomalies. The ridge-trough area, west of long 105°30' W., is characterized by anomalies whose maximum horizontal dimensions are greater than 8 km. The Front Range area, between long 105° and 105°30' W., is characterized by anomalies that have maximum dimensions of 8 km or less. The Great Plains area, east of long 105° W., shows anomalies mostly having maximum dimensions greater than 15 km. To some degree these magnetic differences reflect differing geologic terranes in the quadrangle, and, although the classification is not perfectly rigorous, it lends some physical basis for organizing the presentation of the aeromagnetic data.

Profile A′–A″

The model of subsurface structure along profile A′–A″ (fig. 5) consists of finite-length, two-dimensional bodies perpendicular to the profile. The magnetic susceptibility (dimensionless SI units) is shown for each of the bodies; permanent magnetization is ignored. To approximate the depth of the Curie isotherm (zero magnetization), each body terminates at 30 km below sea level. Each body is of finite length and is bounded perpendicular to the profile by material of susceptibility 0.038. This susceptibility was obtained by least-squares fitting as will be described below, but the geometry of the bounding body was held fixed, topography along the profile defining its upper surface. Bodies at both ends of the profile, including the lateral bounding bodies, project 10,000 km from end points A′ and A″.

We made computations using a program that accounts for finite strike length of the model bodies by applying corrections (Cady, 1980; Shuey and Pasquale, 1973) to the field calculated for infinite strike-length bodies (Talwani and Heirtzler, 1964). The procedure was to specify the model geometry and compute by least squares the susceptibility that produces the best fit of computed magnetic field to the observed data. Geometries were altered until a reasonable model was obtained in terms of field fit, susceptibilities, and geologic structure. Other combinations of geometry and susceptibilities could be found that would produce a field fitting the data equally well. The inferred magnetic susceptibilities for selected important units are summarized in table 4. The "observed data" are interpolated from the data grid used for contouring map *A*. Interpolation was done numerically using a bicubic spline curve.

Sedimentary units in the San Luis Valley, the Sangre de Cristo Mountains, the Wet Mountain Valley, and the Florence basin are assumed to have zero susceptibility and are not explicit bodies in the model

In the model, the westernmost body (1) has the highest susceptibility, 0.091. This body forms the floor of the west side of the San Luis Valley. The body is interpreted to consist of volcanic rocks associated with the San Juan volcanic rocks exposed west of the San Luis Valley. The topographic expression of the San Luis Valley extends 8 km beyond the west end of profile A′–A″, but the model indicates near-surface basement at 0 km. The maximum depth to the basement in the San Luis Valley is modeled at 1.8 km at a location 11 km along the profile; this is 1.5 km west of the low axis d (map *B*).

Body 2 forms the eastern floor of the San Luis Valley and produces the anomaly at 18 km that corresponds to the southern tip of feature D, a magnetic high. Feature D follows an Early Proterozoic metamorphic unit (Xfh) that crops out along the western margin of the Sangre de Cristo Mountains north of profile A′–A″, but there is no corresponding magnetic high associated with the Xfh unit south of the profile. South of the profile, Proterozoic units (Xg, Yg, Xfh) crop out along the western margin of the Sangre de Cristo Mountains. The relative amplitudes of magnetic anomalies associated with exposures of these three units (see the discussion of features H and M) indicate that they rank from low to high susceptibility as gneiss (Xfh), younger granite (Yg), and older granite (Xg). Thus, it is possible that body 2 represents a granite unit (Xg or Yg) rather than gneiss (Xfh). Gravity data along the same profile (Boler and Klein, 1990) shows no anomaly corresponding to the magnetic anomaly at 18 km, but, rather, shows a steep gradient approaching a minimum for the San Luis Valley. Outcrops of Precambrian rocks elsewhere along feature D are generally associated with a magnetic high, which suggests that the 18-km magnetic anomaly is related to a buried fault contact of Precambrian rocks against nonmagnetic Paleozoic sedimentary rocks. However, the possibility of an intrusion controlled by the Sangre de Cristo fault is not ruled out as the cause of this magnetic anomaly.

The boundary between bodies 2 and 3 at 19.2 km coincides with the Sangre de Cristo fault, a normal fault bounding the west side of the Sangre de Cristo Mountains. Body 3 forms the basement of the Sangre de Cristo Mountains, an intensely faulted and folded range that is composed predominantly of Paleozoic sedimentary rocks and is marked by a magnetic low. The basement (body 3) is modeled to be closest to the surface at the Sangre de Cristo fault and to reach a maximum depth of 1.8 km at 35 km along the profile, coincident with the Alvarado fault at the western edge of the Wet Mountain Valley. On the basis of the inferred increasing susceptibilities of the units Xfh, Yg, Xg mentioned above, the lower susceptibility of body 3 relative to body 2 indicates that body 3 may be composed mainly of the metamorphic unit (Xfh). The gravity profile (Boler and Klein, 1990) shows a high at 27 km, where the magnetic profile shows a low. The gravity high at 27 km is presumed to be caused by the Sangre de Cristo uplift capped by dense but nonmagnetic Paleozoic sedimentary rocks.

Body 4, extending between the Westcliffe fault at 41 km and the Ilse fault at 65 km, is modeled as being at or near the surface between 45 km and 57 km. The magnetic high of feature J is caused by the relatively high susceptibility of this body. Body 4 is interpreted to be a Cambrian alkalic intrusive complex having mafic derivatives (see the discussion of feature J) similar to the McClure Mountain Complex (Shawe and Parker, 1967). Much of the misfit between the model and the observed data in this area is related to anomalies 40–43, whose sources are not explicitly included in the model. Body 4 is modeled as sloping beneath the western edge of body 5, which is representative of the less magnetic gneiss unit (Xfh). The gneiss unit dominates the outcrop pattern above body 4, but the magnetic data suggest that it is not the dominant material in the subsurface. Body 4a represents outcrops of volcanic sedimentary rocks.

Body 6, between 65 and 73.2 km, coincides with the outcrop of older granite (Xg) in the Wet Mountains. The outcrop pattern suggests the older granite has limited extent, so this body is modeled to be 10 km long perpendicular to the profile and is bounded perpendicular to the profile by body 7.

Body 7 also forms the basement of the Florence basin region. Body 7 has low susceptibility and is interpreted to consist of Early Proterozoic gneiss (Xfh) on the basis of exposures in the Wet Mountains. The maximum depth to basement of the Florence basin is 2.6 km at 78 km along the profile.

Body 8, at the east end of the profile, was required to fit the observed increase in magnetic values east of the Florence basin. This body has a higher susceptibility than bodies 6 and 7 and may be composed of Proterozoic granite (Yg or Xg). Samples of the younger granite (Yg) from outcrops in the Wet Mountains have a magnetite content of 0.5 percent (Boyer, 1962). This corresponds to a susceptibility as high as 0.1 (Grant and West, 1965, p. 367).

The ridge-trough area

The ridge-trough area (fig. 4) is named for the north- to northwest-trending linear ridges and troughs in the magnetic data and similar trends in the physiography. The area includes the southern Mosquito Range, including the Arkansas Hills as defined by Curtis (1960), in the South Park region to the north and the Sangre de Cristo Mountains bounded by the San Luis and the Wet Mountain Valleys in the south (fig. 4). The faults controlling the San Luis Valley and the Sangre de Cristo Mountains have had Neogene movement associated with formation of the Rio Grande rift (Tweto, 1979b).

The mapped geology in this province shows Precambrian granitic and metamorphic rocks in the mountain ranges and in the Arkansas River Valley, Paleozoic sedimentary rocks along the crests of the Sangre de Cristo Mountains and the Mosquito Range, Cretaceous and Tertiary volcanic rocks in South Park, Tertiary intrusive rocks within the Sangre de Cristo Mountains, and Quaternary sediments in the San Luis Valley and Wet Mountains Valley. Mining districts (Marsh and Queen, 1974; Vanderwilt and others, 1947) are located in the Paleozoic sedimentary rocks of the Sangre de Cristo Mountains and in the Precambrian metamorphic rocks of the Mosquito Range and the Arkansas River Valley.

Feature A. This feature is a distinct magnetic high formed by a clustering of major anomalies; it coincides geographically with the southern Mosquito Range (fig. 4). Anomalies 1 and 1a correlate with outcrops of a Cretaceous granodiorite that Wrucke and Dings (1979) infer to be a laccolith on the basis of the dips of its basal contact. Mineralization there in the Calumet district occurs in veins in the intrusion.

A three-dimensional magnetic model of the intrusive body was constructed in order to determine whether the magnetic data are consistent with the laccolith interpretation. Figure 6*A* shows the residual magnetic field in the area formed from the digitized magnetic data of area 1 (see fig. 1) interpolated into a grid having 1-km intervals; a regional correction was made by subtracting a best-fitting plane surface from the data grid. Figure 6*B* shows the topography of the area along with an outline of the model and the area of outcrop of early Tertiary and Late Cretaceous intrusive rocks (TKi). The model extends from the topographic surface down to the elevations indicated.

Figure 6*C* shows the computed magnetic field assuming a susceptibility of 0.080, and figures 6*D*, *E*, and *F* show profiles across the model. The computer program that was used to calculate the magnetic field of the body is described by Blakely (1981). The final model was obtained by varying (1) the plan outline of the body within the boundaries of the actual outcrop area of the intrusion, (2) the magnetization, and (3) the depth to the bottom surface. Other combinations of body geometry and magnetization could be found that would produce a magnetic field fitting the observed field equally well.

The modeling shows the magnetic data to be consistent with a laccolith intrusion. The thickest part of the body lies between lat 38°36' and 38°40' N. Thinning of the intrusion to the north and south of this central section (see fig. 6*F*) is required to match the lower amplitude of the observed field away from anomaly 1. Parts of the outcrop area extending beyond the heavy lines in figure 6*B*, including that part of the outcrop north of lat 38°42' N., must be thin or a separate facies that has a lower magnetic mineral content, because these areas of the intrusion do not contribute to the observed anomaly. The modeled susceptibility (0.080) indicates that the magnetic mineral content of the major part of the body is abnormally high for typical granodiorite, but it approaches that typical of mafic plutonic rock (Grant and West, 1965, p. 367).

The source elevations computed for anomalies 1 and 1a (table 1) are in qualitative agreement with the model. The source elevation of 2.5 km computed for anomaly 1a is close to the topography, whereas the source elevation of 1.98 km for anomaly 1 is within the thickest part of the modeled laccolith.

Anomalies 2 and 3 coincide with outcrops of Early Proterozoic granite (Xg). Anomaly 2 extends 3 km east of the granite outcrop area, and this indicates that the Precambrian granite unit extends beneath the Tertiary valley sediments east of the Mosquito Range.

Feature B. This feature, characterized by elongated magnetic highs separated by magnetic troughs, encompasses the southern part of South Park, an intermontane basin lying between the Front and Mosquito Ranges (fig. 4). The major geologic units in this area consist of Tertiary volcanic and sedimentary rocks (Td, Tos, Tpl). Compared to neighboring mountain ranges, the topography is gentle, having a relief of about 0.7 km. The anomalies have maximum horizontal extents of 8–15 km and amplitudes generally less than about 200 nT (amplitudes here refer to the difference between the minimum and maximum contours that define the anomaly).

Magnetic trends a and b define two synclinal structures. Low 4 coincides with the northern section of trend a, which lies 1–4 km west of a synclinal axis mapped in the sedimentary units south of Antero Reservoir. Trend b is centered on the axis of low 7. A drill hole at lat 38°59' N., long 105°38' W., within anomaly 7, encountered Precambrian basement at a depth of 1.75 km (Tweto, 1978).

Highs 5, 6, 9, and 10 are inferred to be caused by Precambrian basement highs within the Tertiary sedimentary rocks and volcanic rocks of the Thirtynine Mile volcanic field. Local exposures of Precambrian rocks support this inference. The basement highs are inferred to be fault controlled on the basis of the elongate, steep-sided nature of the anomalies and the existence of several faults in the area. Computed source depths below the surface for these anomalies range from 0.1 km for anomaly 10 to about 1.5 km for anomaly 9.

Anomalies 8 and 8a (features B and H) are lows; the steepness of the gradients and the amplitudes of the anomalies are consistent with reverse magnetization (that is, remanent magnetization having an inclination above the horizontal) of andesitic flows of the Thirtynine Mile Andesite. Anomaly 8a is a more distinct low on the original maps (fig. 1) than on the smoothed data presented here. Graebner (1967) has documented reverse magnetization in some of these flows. Depth to source calculations indicate that the anomaly sources are near or at the surface.

Feature C. This feature is characterized by a general magnetic low and by broad, elongate, subdued anomalies that have amplitudes of only 20–40 nT. The feature is unique because this is the only area of the Pueblo quadrangle where outcrops of Precambrian granitic rock are not associated with positive anomalies of 5–10 km horizontal extent. Lows 11 and 12 occur partly within metamorphic (Xfh), and granitic (Yg and Xg) units, all of which cause highs elsewhere in the quadrangle. Anomaly 14 (a protrusion of feature E extending into feature C) is a high over part of the granitic Xg unit, but the high does not follow the outcrop to the north or east. Anomaly 13 is the only magnetic low in feature C that can be attributed reasonably to the occurrence of nonmagnetic Paleozoic and Tertiary sedimentary rocks. Elevation variation and average surface elevation within feature C are comparable to the De Weese Plateau to the southeast (feature J), where positive anomalies of small dimensions occur, so the topography cannot account for the lack of anomalies. Alteration to the extent that magnetic minerals have been largely destroyed is possible, but there is no supporting geologic evidence. Further investigation is required to determine the cause and significance of the unique magnetic character of this feature.

Elkhorn-Currant Creek-Ilse fault gradient. A steep north-trending magnetic gradient at approximately long 105°30' W., separates the anomalies of features B and C from the anomalies of the Front Range (feature H). A gravity gradient exists in the same position (Boler and Klein, 1990). At the northern edge of the quadrangle, the magnetic gradient trends north-northwest, coincident with the southern extension of the Elkhorn fault into the quadrangle. Between Elevenmile Canyon Reservoir, to the southeast, and Guffey, to the south, the gradient lies within the Thirtynine Mile volcanic field. South from Guffey, the gradient is coincident with segments of the Currant Creek-Ilse fault for about 25 km.

This gradient is inferred to be caused by the Elkhorn fault or a related fault system. The existence of the gradient within the volcanic rocks between Elevenmile Canyon Reservoir and Guffey suggests that the Elkhorn fault continues south from Elevenmile Canyon Reservoir beneath the volcanic rocks to Guffey. This fault or fault system is a probable crustal conduit for the magma that created volcanic rocks at Guffey and Thirtynine Mile Mountain; the lavas and related volcanic sedimentary rocks from these two volcanic centers have probably buried the fault trace.

Feature D. This is a magnetic high that encloses anomalies 15, 16, and 17, and it marks the partly exposed Precambrian rocks on the western flank of the Sangre de Cristo Mountains. The feature extends southwest of the mountain range into the San Luis Valley, to indicate an extension of relatively shallow Precambrian basement beneath the valley sediments. The southern part of this feature dies out at about lat 38°09' N. near the magnetic profile A′–A″, where the magnetic basement has been modeled at 0.8 km below the surface.

Feature E. Feature E consists of north-northwest-trending anomalies in the Sangre de Cristo Mountains and the Wet Mountain Valley. The elongate magnetic low (trend c) over the Sangre de Cristo Mountains reflects the low magnetization of Paleozoic sedimentary rocks. A dipolar anomaly (18) is presumably caused by a Tertiary felsic intrusion that is partly exposed on the crest of the range. High 19 on the western flank of the mountains is apparently caused by outcrops of Early Proterozoic granitic rocks (Xg). Anomaly 14a is a high located east of the mountain range and is coincident with Quaternary sediments of the Wet Mountain Valley. This anomaly is on a linear magnetic high that includes anomaly 14 to the northwest, and together they indicate that the source of anomaly 14 (Xg) continues at shallow depth in the basement of the Wet Mountain Valley. The Cotopaxi mineral district is centered on the northeastern flank of this linear high. Profile model

A′–A″ (fig. 5) shows that the Sangre de Cristo Mountains and the Wet Mountain Valley may be underlain by a continuous magnetic body, probably the metamorphic rock unit (Xfh).

Features F and G. The San Luis Valley (feature F) is marked by a magnetic trough (trend d) along the west side of the Sangre de Cristo Mountains. The magnetic field increases southwest of this trough to the high of feature G; this indicates an uplifted and probably tilted block beneath the valley fill. The magnetic model computed along profile A′–A″ indicates that this block approaches the surface at the west end of the profile and is at a maximum depth of 1.8 km, about 1.5 km west of trend d.

The Front Range area

The Front Range area (fig. 4) is defined here from its general magnetic signature of anomalies having horizontal dimensions of 8 km or less. It coincides with part of the Front Range uplift (Eardley, 1968) that comprises the principal north-south mountain mass of the southern Rocky Mountains abutting the Great Plains (Fairbridge, 1975, p. 631). The physiography of the northern half of the Front Range area is dominated by Pikes Peak. The Wet Mountains are a narrower and topographically lower en echelon extension of the Front Range southwest of Pikes Peak (Curtis, 1960). Flanking the Wet Mountains on the east is the Florence basin, a synclinal structure that connects with the Canon City embayment. The Front Range and Wet Mountains are Laramide-age features bounded on the east by normal or high-angle reverse faults. Neogene movement has been documented on many of these faults (Taylor, 1975). The Pikes Peak and Wet Mountains uplifts have exposed large areas of Precambrian granitic and metamorphic rocks. However, Tertiary volcanic rocks and intrusions host most of the metallic mineral districts within the Front Range area. The beryllium and tungsten deposit in Precambrian granite at Lake George on the northern border of the quadrangle is an exception. Paleozoic sedimentary rocks are uncommon in the area. Cretaceous sedimentary rocks crop out in the Florence basin. Several mafic-alkalic intrusive complexes of Cambrian age crop out in the De Weese plateau and are associated with thorium mineralization in carbonatite dikes (Christman and others, 1959).

Feature H. Feature H is a triangular magnetic high consisting of numerous major anomalies southwest of Pikes Peak. The average residual magnetic intensity of this feature is significantly greater than that of the neighboring features, and the transitional gradients are rather steep and linear.

Five Proterozoic units crop out within the plateau: the metavolcanic and metasedimentary rock units (Xfh, Xb, and Xq) and the granitic rock units (Xg and Yg). The Early Proterozoic granite of the Routt Plutonic Suite (Xg, 1.7 b.y.) is consistently associated with high-amplitude anomalies, including anomalies 20, 28, 30–34, 36, and 37, whose source depths are estimated to be very close to the topographic surface. The Middle Proterozoic granite of the Berthoud Plutonic Suite (Yg, 1.4 b.y.) is the inferred source of anomalies 22, 24, and 25. These anomalies (22, 24, and 25) have amplitudes of 100-140 nT compared to 140–200 nT for anomalies of the same areal extent (34 and 36) caused by the older granite (Xg). The exposed younger granite (Yg) in the area surrounded by anomalies 25–28, 33, and 34 shows no distinctive anomaly, which indicates that the younger unit (Yg) is generally less magnetic than the older unit (Xg). Except for anomaly 27, the metamorphic rock unit (Xb) is not associated with anomalies.

Low 26 occurs in Tertiary volcanic and volcanic sedimentary units. The low may be due to the presence of reversely magnetized volcanic rocks or to lower magnetization of the Tertiary units compared to the surrounding Precambrian units.

Low 29 is coincident with an east-trending topographic depression containing Cretaceous sedimentary rocks and Early Proterozoic quartzite (Xq). Both the depression and its contents would cause a magnetic low relative to the magnetic granite unit (Xg) that surrounds the anomaly.

The Tertiary volcanic rocks near Cripple Creek (anomalies 35 and 35a) occur at the intersection of contacts between the granites of the Berthoud Plutonic Suite (Yg, 1.4 b.y.), the Routt Plutonic Suite (Xg, 1.7 b.y.), and the Pikes Peak batholith (Yp, 1.0 b.y.) and the Early Proterozoic metamorphic unit (Xb). The low of anomaly 35a occurs in the region of the Cripple Creek volcanic center and mineral district. Kleinkopf and others (1970) have interpreted the gravity and magnetic anomalies of the Cripple Creek area to be the result of a volcanic collapse structure. Anomaly 35 is a low coincident with exposed ash flows and tuffs extending from the Cripple Creek center; it may signal additional alteration and mineralization in the vicinity. The lows 21, 23, 23a, and 38 occur in relationship to the gradient caused by the Middle Proterozoic Pike's Peak Granite with remarkable similarity to the relationship of low 35a to the gradient. The possibility that these lows reflect conditions akin to those associated with the rocks and alteration of the Cripple Creek area (35a) is intriguing, but there is no geologic evidence in support of such an inference.

Feature I. The primary part of this feature is a deep low, which corresponds in part to the exposed Pikes Peak Granite. Pratt and Zietz (1973) have suggested that the low results from reverse magnetization of either the batholith or a mafic body beneath the batholith. However, paleomagnetic measurements of samples of the Pikes Peak Granite show it to be very weakly magnetic (10^{-2} A/m magnetization, 0.002 susceptibility) with shallow but positive inclinations for the remanent magnetization (Spall, 1970). This excludes the possibility of reverse magnetization for the Pikes Peak batholith itself. Further, the steep magnetic gradient coincides with the contact between Pikes Peak Granite and the older rocks to the west, and this gradient would occur only if the surface contact were indicative of a major fault that also formed the boundary of the suggested deeper mafic body. Such a fault cannot be ruled out, but the surface contact has been mapped as a fault only along a 5-km section. Finally, the positive gravity anomaly that would be expected in association with a proposed mafic body is not observed (Boler and Klein, 1990).

A two-dimensional model of the anomaly along profile B′–B″ (fig. 7) was constructed in order to determine whether the magnetization contrast between granitic rocks of the Pikes Peak batholith (Yp) and the more strongly magnetic granitic rocks of the Berthoud Plutonic Suite (Yg) and the Routt Plutonic Suite (Xg) to the west could account for the magnetic low. Procedures were similar to those described for profile A′–A″. The model consists of a magnetically susceptible body representing the granites (Yg and Xg) west of the nonsusceptible granites of the Pikes Peak batholith (Yp) (the 0.002 susceptibility of Pikes Peak Granite as measured by Spall (1970) is considered negligible). The body to the west is bounded at the top by topography, extends downward to 30 km below sea level, and is 140 km long perpendicular to the profile. A second susceptible body east of the Rampart Range fault (fig. 4) was necessary. The body to the east extends downward from 1.5 km below the surface to 30 km below sea level and is 80 km long perpendicular to the profile. The susceptibilities of the two magnetic bodies, as determined by least-squares fitting of the model response to the observed data, were found to be 0.026 for the western body and 0.089 for the eastern body. The model demonstrates that the low can be accounted for without recourse to reverse magnetization. The susceptibility determined for the granite (0.026 for units Xg and Yg) is reasonable for rocks of granitic composition (Grant and West, 1965, p. 366).

Highs 39 and 54 are on the northeast side of the Pikes Peak magnetic low; 39 lies over the outcrop area of Pikes Peak Granite, but both anomalies have estimated source depths of more than 1.4 km below the topography. These anomalies are inferred to be caused by differentiated parts of the batholith or later intrusions.

Feature J. This plateaulike magnetic high encompasses three areas of Cambrian mafic-alkalic intrusive complex exposures (Ꞓam) within the Early Proterozoic metamorphic unit (Xfh) of the De Weese plateau. Distinct magnetic anomalies coincide with each of these three areas of Cambrian intrusions. Anomalies 40a, b, and c are caused by the Middle Cambrian McClure Mountain Complex and mafic-ultramafic complex at Iron Mountain (described by Shawe and Parker, 1967). Magnetic measurements of samples from carbonatite dikes and syenitic intrusions at McClure Mountain show magnetizations on the order of 10^{-2}A/m (corresponding to a susceptibility of 0.002), too weak to be the source of the anomalies (R. L. Reynolds, personal commun., 1979). However, associated mafic rocks show magnetizations of 10 and 100 A/m (corresponding to susceptibilities of 0.2-2.0), which indicate that the mafic rocks account for the observed magnetic anomalies. The fact that the three anomalies encircle the main intrusion indicates that the periphery of the intrusion is more mafic than the center. Depth calculations show that sources are close to the surface.

High 41, coincident with the Gem Park Complex, a mafic-ultramafic intrusion (fig. 4) described by Parker and Sharpe (1970), has the largest amplitude of any anomaly associated with the Cambrian intrusions. Anomaly 43 is a dipolar anomaly coincident with the Cambrian syenite complex at Democrat Creek (fig. 4) (Scott and others, 1978). The negative part of this anomaly is larger both areally and in amplitude than the positive part, so the magnetization of the stock has a negative inclination. Magnetic measurements of pyroxenites from this outcrop show magnetization of 1 A/m (corresponding to a susceptibility of 0.02) and shallow to negative inclinations; syenites from the same area show magnetizations of 10^{-1}A/m (corresponding to a susceptibility of 0.002) (R. L. Reynolds, personal commun., 1979). The computed source depth (0.3 km below the surface) suggests that mafic derivatives of the intrusion are relatively shallow.

High 42 occurs within the plateau high, but unlike highs 40, 41, and 43, it is not coincident with any surface exposure of mafic-alkalic intrusions. The estimated source depth for anomaly 42 indicates a shallow source; an intrusion is the probable source body.

High 44 lies between the Silver Cliff and Rosita Hills volcanic centers. The low-level data (fig. 1) show this anomaly as two separate highs. The eastern high corresponds with the location of the Rosita Hills volcanic center. The western part of the anomaly extends south of the Silver Cliff volcanic rocks over the sediments of the Wet Mountain Valley. The Silver Cliff volcanic center displays a magnetic low that Kleinkopf and others (1979) interpret to be due to a graben filled with magnetically altered volcanic rocks and volcanic sediments. They interpret the high to the south to be due to buried Early Proterozoic metamorphic rocks (Xfh).

Although feature J roughly coincides with the Early Proterozoic metamorphic unit (Xfh) of the De Weese plateau, the boundary gradients to the northwest, northeast, and southeast are well within the outcrop area of the unit (Xfh) and do not follow known geologic contacts. The southwestern edge of this plateau high extends to the Alvarado fault at the eastern boundary of the Sangre de Cristo Mountains. The shape of the northern half of feature J is determined by the anomalies caused by the mafic-alkalic intrusions; this implies that much of the plateau high may be caused by a body of similar composition and that the surface exposures of the McClure Mountain and Gem Park Complexes, and the seyenite complex at Democrat Creek are only a fraction of a larger body. The gentler southeast and southwest gradients of the feature, along with fewer major anomalies to the south, indicate that the causative body is deeper to the south or that a different body causes the southern extension of feature J. Both of these possibilities agree with the lack of outcrops to the south. The southeastern gradient of feature J passes directly through the Rosita Hills volcanic center and may reflect a crustal weakness that controlled the emplacement of these volcanic rocks. Similarly, the volcanic rocks at lat 38°15' N., long 105°35' W., east of the Gem Park Complex, lie along the western boundary gradient and may have formed from magma that rose along a similar crustal weakness marked by this gradient. The northeast boundary of the plateau follows part of the trend of the Ilse fault and lies west of the crest of the Wet Mountains. The Early Proterozoic metamorphic unit (Xfh) is apparently nonmagnetic, because the crest of the Wet Mountains is marked by the magnetic gradient descending from feature J to the low of feature N. This gradient is disturbed (anomalies 45 and 46) only where the granitic unit (Xg) crops out (Scott and others, 1978).

The model of profile A′–A″ (fig. 5) shows that the causative body for feature J (body 4) is bounded on the east by the Ilse fault, which is interpreted from the model as a normal fault with the Wet Mountains uplifted. Body 4 is buried by body 5 north of high 43. The model shows that bodies 6 and 7, making up the Wet Mountains, have lower susceptibilities than body 4.

Feature K. Feature K is the southwestern boundary of feature J; it occurs over the western half of the Wet Mountain Valley. This feature marks the southwestern transition zone from feature J to the low of the Sangre de Cristo Mountains (magnetic trend c of feature E). Anomalies of horizontal dimensions less than 10 km, which characterize the northeastern part of feature J, are absent just east of feature K. Some attenuation of anomalies is expected over the Wet Mountain Valley, simply due to the greater source depth on the valley floor; it is also possible that the valley floor is composed of lower susceptibility material than the mafic-alkalic intrusive body. In the model of profile A′–A″(fig. 5), the western boundary of the mafic-alkalic intrusive body of feature J is the Westcliffe fault, located about 7 km east of the Alvarado fault. The deepest point of the valley floor is at the Alvarado fault, where the valley fill is 1.8 km thick. A resistivity profile crossing the valley at lat 38°05' N., (Zohdy and others, 1971) shows the valley floor tilting westward from a depth of 600 m at 5 km east of the Westcliffe fault to a depth of 1.8 km at a point 2 km east of the Alvarado fault.

Feature L. This feature is a magnetic low that separates features J and M and that partly corresponds with the axis of magnetic trend e. Trend e roughly follows North Hardscrabble Creek, connecting low 49 to the east with outcrops of Tertiary volcanic sedimentary rocks (low 48) to the southwest. High 47 apparently results from a magnetization contrast between the metamorphic unit (Xfh) and the Quaternary sediments of the Wet Mountain Valley to the west.

Feature M. This is a plateaulike magnetic high that encloses anomalies 50-53 in the Deer Peak area of the Wet Mountains. Highs 50 and 52 have the largest amplitudes on the magnetic map. Anomaly 50 has the largest amplitude on the State aeromagnetic map (Zietz and Kirby, 1972 a and b) and thus generates interest as to its source. A question arises in regard to the influence of the large topographic variations that occur in conjunction with this anomaly.

The topography for feature M is shown in figure 8*A*. The computed magnetic field produced by this topography (an assumed susceptibility of 0.023) is shown in figure 8*B*, and the observed residual field is shown in figure 8*C*. It can be seen that the amplitudes of the observed anomalies would not result from topography alone, unless the terrain had susceptibility of approximately 10 times greater (0.23). This is well above the average of 0.006 for rocks of granitic composition (Grant and West, 1965, p. 366), such as the granite (Yg) that crops out in the eastern half of feature H, and well above the modeled susceptibility (0.086) of the model of anomaly 50 (discussed below). It can also be seen that high 50 correlates poorly in position and shape with the magnetic anomalies computed from the topography. High 52 correlates with the position of the computed topographic magnetic anomaly at lat 38°00' N., long 105°07' W., but the observed anomaly is elongated in the north-south direction in contrast to the east-west elongation of the computed topographic anomaly. We conclude that the topographic variations have only a minor role in producing the observed magnetic anomalies.

The source of the observed residual magnetic field of high 50 (replotted in fig. 9*A*) was modeled as a vertical cylinder (approximated by an eight-sided, equiangular, vertical prism) in order to approximate the symmetry seen in the observed data (fig. 8*C*). The field of the model was computed using the method of Talwani (1965). The radius and the depths to the top and the bottom of the cylinder were varied, and the susceptibility for each case was determined by least squares to obtain the best fit between computed and observed fields. The best fitting field is shown in figure 9*B*; profiles across the model are shown in figures 9*C* and *D*. The best fitting model has a susceptibility of 0.086, has a radius of 2.5 km, and extends from 3.05 km above sea level to 3.05 km below sea level.

Figure 10 shows the relationship among susceptibility, radius, and depth-to-top for cylinders that fit the observed anomaly (high 50) nearly as well as the model of figure 9*B*. The model marked by the circle corresponds to the best fitting model shown in figure 9*B*. Although all of these models satisfy the observed field, the models that have lower susceptibilities are more likely to be correct. The susceptibility of the best fitting model is two times higher than the average susceptibility for gabbroic rocks (Grant and West, 1965, p. 366). A narrow, magnetite-rich ultramafic plug is possible, but a larger radius gabbroic mass near the surface is more probable. Taylor (1974) has mapped gabbroic rocks in the vicinity of anomaly 50. The close proximity of highs 50, 52, and 53 suggests that their sources may be compositionally and genetically similar.

Feature N. This deep low northeast of the Wet Mountains coincides in the east with the nonmagnetic sediments of the Florence basin syncline. The axis of the magnetic low (trend f) lies just west of the syncline axis and within the gneiss unit (Xfh) of the Wet Mountains crystalline block, which indicates the relatively nonmagnetic nature of that unit. Highs 45 and 46 are coincident with the older granitic unit (Xg) (Scott and others, 1978). The estimated source depths of these two anomalies are probably unreliable because of the interference of the magnetic gradient between features J and N.

Great Plains area

The Great Plains area (Fairbridge, 1975, p. 557) consists of the flat-lying area east of about long 105°00' W. Quaternary sediments cover more than 50 percent of this area within the Pueblo quadrangle; Cretaceous sedimentary units make up the remaining outcrop area. Sedimentary formations are thickest in the Denver basin at the north end of the quadrangle. Faults and folds in the sedimentary rocks parallel the mountain front south of Pikes Peak. The Great Plains area is characterized by low-amplitude anomalies that have maximum horizontal dimensions on the order of 25 km. The subdued magnetic anomalies are due partly to the wide flightline spacing (8 km). In addition, the high altitude of the survey (3 km above the topography) and the thickness of the sedimentary layers above the magnetic basement rocks result in a source-sensor separation that is four to five times greater in the plains area than in the mountains.

Features 0, P, Q, and R. Exposed Proterozoic units in the Front Range area can be ranked in order of decreasing magnetization as older granite (Xg), younger granite (Yg), gneisses (Xfh), and rocks of the Pikes Peak batholith (Yp) on the basis of magnetic anomaly characteristics discussed previously. This ranking provides a guideline for identifying possible basement units beneath the sedimentary rocks of the Great Plains area. The low of feature P (lows 57–59) extends eastward from Pikes Peak and may indicate basement rocks of similar composition to those of the Pikes Peak batholith (Yp). Features 0 (anomalies 55 and 56) and Q (anomalies 60-62) are highs likely caused by basement similar to units including granitic rocks of Berthoud (Yg) or Routt (Xg) Suites. Note that feature Q appears to be trending into feature H. Profile model A′–A″ indicates that a low susceptibility unit, probably gneisses (Xfh), exists in the basement below feature N. At the boundary between features N and Q, the model shows a body of higher susceptibility that is probably granite (Yg or Xg). The low of feature R (anomalies 63, 64, and 65) is probably related to the gneisses (Xfh) exposed in the Wet Mountains to the west. In fact, the minimum of anomaly 63 (trend f) coincides with an outcrop of gneiss (Xfh).

The east-west magnetic trends imply a similar alignment in the lithologic units. Edwards (1966) compiled a basement lithologic map of Colorado on the basis of drill-hole data. He distinguishes between granitic, metavolcanic, and metasedimentary rocks and shows a wide band of granitic rocks extending from the northwest corner of the State along a northeast trend into the Pueblo quadrangle. His map is poorly constrained within the Pueblo quadrangle north of lat 38°30' N., and the east-west alignment of magnetic lithologic units suggested by the magnetic map does not fundamentally contradict his data.

REGIONAL MAGNETICS AND MINERALIZATION

Case (1967) and Tweto and Case (1972) suggest that magnetic lows can be expected in mineralized areas because of the destruction of magnetic minerals by hydrothermal alteration. Studies in the Cripple Creek area and the Rosita Hills-Silver Cliff area (fig. 4) (Kleinkopf and others, 1970, 1979) have attributed magnetic lows to volcanic-subsidence structures, volcanic breccias, and alteration of the magnetic minerals during episodes of mineralization. Although magnetic lows having dimensions on the scale of mineral deposits will not show up consistently at the map scale presented here, it is possible to comment on the regional relationships between magnetic data and mineralization.

The mineralized host rocks within the Pueblo quadrangle (see table 3) are Tertiary volcanic rocks, Paleozoic sedimentary rocks, and Precambrian crystalline rocks. Three of the four mineral districts hosted by Tertiary volcanic rocks (Cripple Creek, Silver Cliff, and Rosita Hills) occur within the Front Range area, whereas the fourth (Guffey) lies on the western geophysical boundary of this area. Tertiary volcanic rocks occur within the ridge-trough area, mainly at Thirtynine Mile and Waugh

Mountains, but associated mineralization is unknown. All of these districts except Silver Cliff lie on or near magnetic gradients that define features J and H. Silver Cliff is located near the northern flank of high 44 within feature J.

Five mineral districts (Turret, Calumet, Crestone, Lake George, and Cotopaxi) occur in Precambrian rocks. All of these districts except Crestone lie on or near moderate to steep magnetic gradients. Crestone is within a broad magnetic low of the Sangre de Cristo Mountains near the south border of the map. Turret occurs on the flank of high 1, but the remaining four districts are not associated with any of the numbered magnetic anomalies shown on the present map.

The Whitehorn district is related to a Cretaceous granitic intrusion that causes anomalies 1 and 1a. The Orient district and the Trout Creek district are located within Paleozoic sedimentary rocks. Both of these districts lie along moderate to weak magnetic gradients, but neither is associated with one of the numbered anomalies on the present map.

Of the thirteen metallic mineral districts in the Pueblo quadrangle, eight (Trout Creek, Lake George, Cripple Creek, Guffey, Calumet, Whitehorn, Cotopaxi, and Rosita Hills; see table 3) lie on or near the major magnetic gradients that define features having dimensions of about 20 km or more. Three of the 13 districts (Turret, Orient, and Silver Cliff) appear to be associated with the smaller dimension anomalies. The major gradients are associated typically with the juxtaposition of rocks of different densities and magnetizations as a result of faulting or large-scale intrusion. The Alvarado fault gradient and the Elkhorn and Currant Creek-Ilse fault gradients are examples of such gradients that coincide with mapped faults. We suggest that these major gradient zones, shown on map *B*, indicate crustal weaknesses that are preferred paths along which magmas and mineralizing fluids may migrate. Therefore, these zones may be the logical focus for future, more detailed mineral exploration.

REFERENCES

Blakely, R. J., 1981, A program for rapidly computing the magnetic anomaly over digital topography: U.S. Geological Survey Open-File Report 81–298, 46 p.

Boler, F. M., and Klein, D. P., 1990, Residual Bouguer gravity and interpretative maps of the Pueblo 1°×2° quadrangle, south-central Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–1419–B, scale 1:250,000.

Boyer, R. E., 1962, Petrology and structure of the southern Wet Mountains, Colorado: Geological Society of America Bulletin, v. 73, no. 9, p. 1047–1069.

Cady, J. W., 1980, Calculation of gravity and magnetic anomalies of finite-length right-polygonal prisms: Geophysics, v. 45, no. 10, p. 1507–1512.

Case, J. E., 1967, Geophysical ore guides along the Colorado mineral belt: U.S. Geological Survey Open-File Report 67–39, 16 p.

Christman, R. A., Brock, M. R., Pearson, R. C., and Singewald, Q. D., 1959 [1960], Geology and thorium deposits of the Wet Mountains, Colorado—A progress report: U.S. Geological Survey Bulletin 1072–H, p. 491–535.

Curtis, B. F., 1960, Major geologic features of Colorado, *in* Weimer, R. J., and Haun, J. D., eds., Guide to the geology of Colorado: Denver, Colo., Geological Society of America, Rocky Mountain Association of Geology, and Colorado Scientific Society, p. 1–8.

Eardley, A. J., 1968, Major structures of the Rocky Mountains of Colorado and Utah, *in* A coast to coast tectonic study of the United States: University of Missouri at Rolla Journal, (V. H. McNutt–Geology Department Colloquium, Series 1), no. 1, p. 79–99.

Edwards, Jonathan, Jr., 1966, The petrology and structure of the buried Precambrian basement of Colorado: Colorado School of Mines Quarterly, v. 61, no. 4, 436 p.

Fairbridge, R. W., ed., 1975, The encyclopedia of world regional geology, Part 1: Western Hemisphere, Encyclopedia of earth sciences V. VIII: Stroudsburg, Penn., Dowden, Hutchinson and Ross, Inc., 704 p.

Graebner, Peter, 1967, Remanent magnetism in major rock units of the Thirtynine Mile volcanic field, central Colorado: Golden, Colo., Colorado School of Mines, M.S. thesis, 165 p.

Grant, F. S., and West, G. F., 1965, Interpretation theory in applied geophysics: New York, McGraw-Hill Book Company, 583 p.

Kleinkopf, M. D., Peterson, D. L., and Gott, Garland, 1970, Geophysical studies of the Cripple Creek mining district, Colorado: Geophysics, v. 35, no. 3, p. 490–500.

Kleinkopf, M. D., Peterson, D. L., and Mattick, R. E., 1979 [1980], Gravity, magnetic, and seismic studies of the Silver Cliff and Rosita Hills volcanic area, Colorado: U.S. Geological Survey Professional Paper 726–F, 17 p.

Marsh, W. R., and Queen, R. W., 1974, Map showing localities and amounts of metallic mineral production in Colorado: U.S. Geological Survey Mineral Investigations Resource Map MR–58, scale 1:500,000.

Parker, R. L., and Sharp, W. N., 1970, Mafic-ultramafic igneous rocks and associated carbonatites of the Gem Park Complex, Custer and Fremont Counties, Colorado: U.S. Geological Survey Professional Paper 649, 24 p.

Pratt, W. P., and Zietz, Isidore, 1973 [1974], Geologic interpretation of the Colorado aeromagnetic map, *in* Geological Survey research 1973, U.S. Geological Survey Professional Paper 850, p. 50.

Scott, G. R., Taylor, R. B., Epis, R. C., and Wobus, R. A., 1978, Geologic map of the Pueblo 1°×2° quadrangle, south-central Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–1022, scale 1:250,000.

Shawe, D. R., and Parker, R. L., 1967 [1968], Mafic-ultramafic layered intrusion at Iron Mountain, Fremont County, Colorado: U.S. Geological Survey Bulletin 1251–A, 28 p.

Shuey, R. T., and Pasquale, A. S., 1973, End corrections in magnetic profile interpretation: Geophysics, v. 38, no. 3, p. 507–512.

Spall, Henry, 1970, Paleomagnetism of the Pike's Peak Granite of Colorado: Geophysical Journal of the Royal Astronomical Society, v. 21, p. 427–440.

Talwani, Manik, 1965, Computation with the help of a digital computer of magnetic anomalies caused by bodies of arbitrary shape: Geophysics, v. 30, no. 5, p. 797–817.

Talwani, Manik, and Heirtzler, J. R., 1964, Computation of magnetic anomalies caused by two-dimensional structures of arbitrary shape, *in* Parks, George, ed., Computers in the mineral industries: Palo Alto, Calif., Stanford University, p. 464–480.

Taylor, R. B., 1974 [1975], Reconnaissance geologic map of the Deer Peak quadrangle and southern part of the Hardscrabble Mountain quadrangle, Custer and Huerfano Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–870, scale 1:24,000.

______1975, Neogene tectonism in south central Colorado, *in* Curtis, B. F., ed., Cenozoic history of the southern Rocky Mountains: Geological Society of America Memoir 144, p. 211–226.

Tweto, Ogden, 1978, Tectonic map of the Rio Grande rift system in Colorado: New Mexico Bureau of Mines and Mineral Resources Circular 163, sheet 1, scale 1:1,000,000.

______ 1979a, Geologic map of Colorado: U.S. Geological Survey Special Map, scale 1:500,000.

______ 1979b, The Rio Grande rift system in Colorado, *in* Reicker, R. E., ed., Rio Grande rift: Tectonics and magmatism: Washington, D. C., American Geophysical Union, p. 33–56.

Tweto, Ogden, and Case, J. E., 1972, Gravity and magnetic features as related to geology in the Leadville 30' quadrangle, Colorado: U.S. Geological Survey Professional Paper 726–C, 31 p.

Vacquier, Victor, Steenland, N. C., Henderson, R. G., and Zietz, Isidore, 1951, Interpretation of aeromagnetic maps: Geological Society of American Memoir 47, 151 p.

Vanderwilt, J. W., and others, 1947, Mineral resources of Colorado: Denver, Colo., Mineral Resources Board, 547 p.

Wrucke, C. T., and Dings, M. G., 1979, Geologic map of the Cameron Mountain quadrangle, Chaffee, Fremont, and Park Counties, Colorado: U.S. Geological Survey Open-File Report 79–660, scale 1:62,500.

Zietz, Isidore, and Kirby, J. R., Jr., 1972a, Aeromagnetic map of Colorado: U.S. Geological Survey Geophysical Investigations Map GP–836, scale 1:500,000.

______1972b, Aeromagnetic map of Colorado: U.S. Geological Survey Geophysical Investigations Map GP–880, scale 1:1,000,000.

Zohdy, A. A. R., Hershey, L. A., Emery, P. A., and Stanley, W. D., 1971, Resistivity sections, upper Arkansas River basin, Colorado: U.S. Geological Survey Water Resources Open-File Report 71–337, 16 p.